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# Human Factors and Performance Concerns for the Design of Helmet-Mounted Displays (Reprint)


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Since the 1970s, the trend in Army aviation has been to rely increasingly on helmet-mounted display (HMD) devices or systems to provide the aircrew with pilotage imagery, flight information, and fire control imagery and symbology. Design specifications for future HMDs must be guided by system parameter criteria convolved with hardware limitations, human performance strengths and weaknesses, and good human factors engineering practices. In this paper, past and ongoing research of HMDs is combined to identify potential sources of performance degradation and health hazards. While recognizing the importance of acoustical and biodynamic issues, the major focus here is on optical and visual issues, which include binocular rivalry, fusion, visual illusions, spatial disorientation, and image quality. Related human factors issues also are discussed.

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# Human Factors and Performance Concerns for the Design of Helmet-Mounted Displays

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**Summary**

Since the 1970s, the trend in Army aviation has been to rely increasingly on helmet-mounted display (HMD) devices or systems to provide the aircrew with pilotage imagery, flight information, and fire control imagery and symbology. Design specifications for future HMDs must be guided by system parameter criteria convolved with hardware limitations, human performance strengths and weaknesses, and good human factors engineering practices. In this paper, past and ongoing research of HMDs is combined to identify potential sources of performance degradation and health hazards. While recognizing the importance of acoustical and biodynamic issues, the major focus here is on optical and visual issues, which include binocular rivalry, fusion, visual illusions, spatial disorientation, and image quality. Related human factors issues also are discussed.

Figure 1. The AH-64 Integrated Helmet and Display Sighting System (IHADSS).

## 1. Introduction

Since the 1970s, the trend in Army aviation has been to rely increasingly on HMD devices or systems to provide the aircrew with pilotage imagery, flight information, and fire control imagery and symbology. The first such system was the AN/PVS-5 series night vision goggle (NVG), circa 1973. By 1989, the AN/PVS-5 had been replaced by the AN/AVS-6 Aviator's Night Vision Imaging System (ANVIS), the first image intensification ($I^2$) HMD designed specifically for Army aviation use. When the AH-64 Apache attack helicopter was fielded in the early 1980s, the head-mounted $I^2$ sensors in NVGs were replaced as the imagery source by a forward-looking infrared (FLIR) sensor, the Pilot's Night Vision System (PNVS), mounted on the nose of the aircraft. Imagery from this sensor is displayed on a miniature 1-inch diameter cathode ray tube (CRT) and optically relayed to the eye. This system is known as the Integrated Helmet and Display Sighting System (IHADSS) (Figure 1). It is a monocular system, presenting imagery to the right eye only. The IHADSS was the first integrated HMD, where the helmet, head tracker, and display were designed as a single system. The success of IHADSS in Army aviation has greatly influenced and contributed to the proliferation of HMD programs [1].

Currently, the Army is developing the RAH-66 Comanche reconnaissance helicopter. This aircraft will utilize a partially overlapped biocular HMD, known as the Helmet Integrated Display Sight System (HIDSS). It consists of an aircraft retained unit (ARU) and a pilot retained unit (PRU). The PRU is the basic helmet with visor assembly. The ARU is a front piece consisting of two image sources and optical relays attached to a mounting bracket. The HIDSS development and validation phase design, which is based on two miniature, 1-inch, CRTs as image sources, provides a 30° (V) by 52° (H) field-of-view (FOV) with a 17° overlap region. However, miniature displays based on flat panel (FP) technologies [e.g., liquid crystal (LC) and electroluminescence (EL)] will very likely replace the CRTs in subsequent program phases.

It is expected that the trend for increasing reliance on HMDs in aviation, as well as in other sectors of the Army, will continue. This paper is intended to serve as both a checklist and a guide for designers of such future integrated helmet and display systems for rotary-wing aircraft. In this paper: 1) salient performance parameters of such systems are identified; 2) recommendations for values of these parameters are suggested, where available, based on past research and the opinions of subject matter experts; 3) human factors engineering and health hazard issues are discussed, and 4) lessons learned from previously fielded U.S. Army HMD systems are summarized. However, this paper is not a cookbook for building an integrated helmet and display system. The design of such a system is strongly dependent on its purpose, user requirements, and the environment within which it is intended to operate.

Melzer and Moffitt [2] describe an HMD as minimally consisting of "an image source and collimating optics in a head mount." For the purpose of this paper, we expand this description to include a visual coupling system, which performs the function of slaving head and/or eye positions and motions to one or more aircraft systems. Figure 2 presents the basic Army aviation HMD as a block diagram in which there are four major elements: image source (and associated drive electronics), display optics, helmet, and head/eye tracker. The image source is a display device upon which sensor imagery is produced. These sources typically have been miniature CRTs or $I^2$ tubes. Other miniature displays based on FP technologies rapidly are becoming alternate choices. The display optics are used to couple the display imagery to the eye. The optic

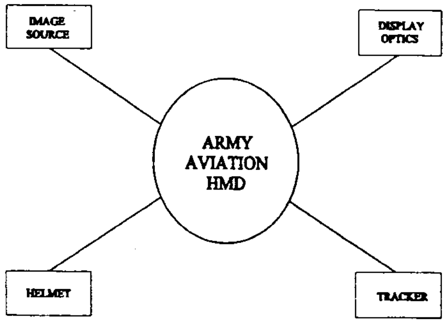


Figure 2. Block diagram of basic Army aviation HMD.

generally magnify and focus the display image. The helmet, while providing the protection for which it was designed originally, serves additionally as a platform for mounting the image source and display optics. The tracking system couples the head/eye line of sight with that of the pilotage sensor(s) (when mounted off the head) and weapons.

An HMD designer must develop a system which is capable of satisfying a large number of widely different and often conflicting requirements in a single system. Such design goals include but are not limited to the following [3]:

- Maximum impact protection
- Maximum acoustical protection
- Maximum speech intelligibility
- Minimum head supported weight
- Minimum bulk
- Minimum CM offset
- Optimum head aiming/tracking accuracy
- Maximum comfort and user acceptance
- Maximum freedom of movement
- Wide FOV
- Minimum obstructions in visual field
- Full color imagery
- Maximum resolution
- High brightness and contrast
- No induced sensory illusions
- Hazard free
- Maximum crashworthiness
- 24-hour, all weather operation
- Minimum training requirements
- Low maintenance
- Low design cost and minimum schedule

From this abridged list of requirements, it becomes apparent that the design of an HMD requires the careful consideration of a multitude of physical parameters and performance factors. In an approach, physical characteristics are replaced by performance figures of merit (FOMs) (Table 1). These FOMs are grouped into natural performance categories: optical system, visual, helmet (with tracking system), and human factors engineering.

## 2. Visual Coupling

One HMD enhancement to mission effectiveness is the providing of video imagery used for pilotage (most effective during night and foul weather missions). This pilotage imagery is generated from sensors. These sensors can either be head/helmet-mounted, as with ANVIS, or aircraft-mounted, as with the FLIRs on the AH-64 Apache and RAH-66 Comanche. With head-mounted sensors, the resulting imagery is inherently correlated with the direction of head line-of-sight. However, to obtain this spatial correlation for aircraft-mounted sensors, it is necessary to slave the sensor to head motion; the sensor must be "visually coupled" to the head. To accomplish this task, a head/eye tracking system is incorporated into the HMD.

Table 1: HMD performance figures-of-merit [4,5].

| | | | |
|---|---|---|---|
| **Optical system** | Prismatic deviation<br>Residual refractive power<br>FOV<br>Percent overlap | Extraneous reflections<br>Biocular channel disparities and misregistration<br>Chromatic aberrations<br>Exit pupil size and shape | Image overlap<br>Static and dynamic MTFs<br>Distortion<br>Spherical/astigmatic aberrations |
| **Visual** | Visual acuity<br>Visual field<br>Ocular responses | See-through luminous transmittance<br>See-through color discrimination | Depth perception and stereopsis<br>Illusionary effects<br>Visual problems |
| **Helmet** | Head supported weight<br>CM offset<br>Impact attenuation<br>Shell tear resistance<br>Earphone/earcup characteristics<br>Real-ear attenuation | Fitting system characteristics<br>HMD breakaway force<br>Anthropometric fitting range<br>Visor optical characteristics<br>Physical-ear attenuation<br>Speech intelligibility | Tracking accuracy<br>Tracking resolution<br>Tracking system update rate<br>Tracking system motion box size<br>Tracking system jitter |
| **Human factors** | Interpupillary distance range<br>Physical eye relief | User adjustments selection and range<br>Equipment compatibility | Training requirements<br>Egress characteristics<br>Fit procedure |

## 2.1 Tracking Systems

Tracking systems with helmet-mounted components must minimize the additional weight, volume, and packaging impacts on the HMD. This is best achieved by using an integrated approach in the HMD design [6]. The various subsystems, e.g., the helmet, optics, etc., still perform their basic functions with minimal compromise to these functions and those of other subsystems. Tracking components which must be helmet-mounted can be modular (add-on), but integrated approaches allow for the imbedding of these components into the helmet shell, thereby optimizing the HMD packaging.

The simplest type of tracking is head tracking, where the position of the head pointing direction is constantly measured. When viewing or tracking objects in the real world, a combination of both head and eye movements is used. [It is an unnatural act to track or point using the head alone. Normal head and eye coordinated motion begins with the eye executing a saccade towards the object of interest, with velocities and accelerations exceeding those of the associated head motion. Consequently, the eye reaches the object well before the completion of the head motion [7].] Eye movements are confined to ±20° about the head line-of-sight. To replicate this viewing mode, more sophisticated visually coupled systems (VCSs) may augment head tracking with eye tracking.

Tracking systems must provide defined measures of accuracy. System parameters include motion box size, pointing angle accuracy, pointing angle resolution, update rate (of tracker, not display), and jitter. The motion box size defines the linear dimensions of the space volume within which the head tracking system (HTS) can accurately maintain a valid line-of-sight. The box is referenced to the design eye position of the cockpit. It is desirable that this box provide angular coverage at least equal to that of normal head movement, i.e., ±180° in azimuth, ±90° in elevation, and ±45° in roll [8]. The motion box size for the AH-64 IHADSS is 12 inches forward, 1.5 inches aft, ±5 inches laterally, and ±2.5 inches vertically from the design eye position. From a human factors viewpoint, it is important that the motion box be able to accommodate multiple seat positions and aviator posture variances.

Pointing accuracy, also referred to as static accuracy, usually means the performance within the local area of the design eye position and for an angular coverage of ±30° in azimuth and ±70° in elevation, i.e., the envelop where the head spends most of its time [8]. In a laboratory setting, current systems can provide excellent static pointing accuracies of 1 to 2 milliradians (mr) (at least in azimuth and elevation, roll accuracy is more difficult to achieve). Measured accuracies in actual aircraft are more typically in the 3 to 4 mr range. Maximum static accuracy is limited by the system's pointing resolution. Pointing resolution refers to the smallest increment in head position (or corresponding line-of-sight angle) which produces a difference in HTS output signal level. One recommendation [4] states that the HTS should be able to resolve changes in head position of at least 1.5 mm along all axes over the full motion box. HTSs also need to provide a specified dynamic accuracy, which pertains to the ability of the tracker to follow head velocities. Dynamic tracking accuracy (excluding static error) should be less than 30 mr/sec.

HTS update rate performance is an often poorly defined parameter. To be useful, update rate must be defined in terms of the sampling rate and the tracking algorithm [8]. Sampling rates of >100 Hz are available. Both IHADSS and HIDSS use a 60 Hz rate. However, if the display update rate is slower than the HTS sampling rate, then these higher rates do not offer an advantage.

Variations in head position output due to vibrations, voltage fluctuations, control system instability, and other unknown sources are collectively called jitter. Techniques to determine the amount of jitter present are extremely system specific.

## 2.2 System (Lag) Delay

For HMDs where the sensor is helmet-mounted, as with ANVIS, the head and sensor are directly coupled and act as one unit. There is no time delay associated with this coupling. However, for aircraft-mounted sensor systems, the very presence of a VCS implies that there will be a delay between the real world and its presentation [9]. This delay is present because the VCS has to calculate the head positions, translate them to sensor motor commands, and route these commands to the sensor gimbal. Then, the gimbal must slew to the new positions and the display must be updated with the new images. If the magnitude of the delay is large enough, several image artifacts may occur: image flicker, simultaneously occurring objects, erroneous dynamic behavior, and/or multiple images [10].

The natural question is: How fast should the VCS be in transferring head motion to sensor motion and then presenting the new imagery? Its answer depends strongly on the maximum slew rate of the sensor gimbal. The inability of the sensor to slew at velocities equal to those of the aviator's head will result in significant errors between where the aviator thinks he is looking and where the sensor actually is looking, constituting time delays between the head and sensor lines-of-sight. Medical studies of head motion have shown that normal adults can rotate their heads +/-90° in azimuth (with neck participation) and -10° to +25° in elevation (without neck participation). These same studies show that peak head velocity is a function of anticipated movement displacement, i.e., the greater the required displacement, the higher the peak velocity, with an upper limit of 352°/sec [11,12]. However, these studies were laboratory-based and may not reflect the velocities and accelerations indicative of the helmeted head in military flight scenarios [13].

However, VCS lags are not the only delays in the presentation of imagery in HMDs. King [14] cites three types of time lags which must be considered in HMD use: Display lag, slaving lag, and sensor/weapon feedback lag. Display lag is defined as the display latency relative to the current helmet line-of-sight and includes the update rate of the tracker and the refresh rate of the display. Slaving lag is defined as the latency of the sensor/weapon line-of-sight relative to the helmet line-of-sight. This includes the tracker computational time, data bus rate, and physical slaving of the sensor/weapon. Sensor/weapon feedback lag is the latency involved in getting the slave command to the slaving mechanism (gimbal). King [14] provides typical values for these three lags as 50, 650, and 150 msec, respectively.

When discussing time delays in HMDs in the display community, it has been customary to use the term "lag" to mean the time between when the head moves and when the presented image changes to reflect this movement. The frequency at which new display image frames are presented (display refresh) is called the update rate. However, other disciplines do not adhere to this format, and it is wise to precisely define all delay times used with HMDs and VCS.

So and Griffin [15] investigated the effects of lag on head tracking performance using lag times between head movement and target image movement of 0, 40, 80, 120, and 160 msec. They found that head tracking performance was degraded significantly by lags greater than or equal to 40 msec (in addition to a 40 msec delay in the display system). A similar study [16],which investigated the effect of system lag on continuous head tracking accuracy for a task of positioning a cursor on a stable target, found performance effects for lags as short as 20 msec (plus 40 msec display system delay).

The studies cited above, and others [17-19], suggest that there is some uncertainty in maximum allowable time delays, ranging from 40 to 300 msec, depending on task and system. Wildzunas, Barron, and Wiley [20] utilized a NUH-60 Blackhawk simulator to investigate the delay issue under a more realistic military aviation scenario. They tested delays of 0, 67, 133, 267, 400, and 533 msec. The delays were inserted into the simulator's visual display. However, while more representative of rotary-wing flight, the displays were panel-mounted, not head-mounted. While finding some performance effects for delays less than or equal to 267 msec, consistently significant effects were found for the 400 and 533 msec delays.

### 2.3 Vibration

Helicopters vibrate and any aviator will tell you that is an understatement. This vibration affects both the aircraft and the aviator. Human response to this vibration has been a more difficult problem to understand and solve than that with the aircraft [21]. The effects of vibration manifest themselves as retinal blur, which degrades visual performance, and as physiological effects, whose resulting degradation is not fully understood [22]. Rotary-wing aircraft differ in their vibrational frequencies and amplitudes and these vibrations are triaxial in nature. However, in general, they have a frequency range in all axes of 0.5-100 Hz. However, the transfer function of these vibrations to the eye is not straightforward. The activity of the vestibulo-ocular reflex stabilizes some of the vibrational transfer, mostly low frequency. However, visual performance degradation still will be present. To further complicate this scenario, the vibrational transfer function to the helmet and HMD is different from that to the eye. While the general influencing factors are the same, e.g., posture, body size, etc, the helmet/HMD mass is also a factor. The result is a very complex frequency and amplitude relationship between the eye and the HMD imagery, which results in relative motion between the imagery and the eye [23].

Viewing collimated (infinity focused) HMD imagery should, in theory, eliminate nonangular vibration effects on visual performance. However, investigations of visual performance with HMDs under the relative motion between the display and the eye due to vibration have shown a number of effects. At frequencies below 10 Hz, reading information off the HMD is more difficult than reading off panel-mounted displays [24], up to tenfold at some frequencies. In an investigation of reading HMD symbology numerals, numerals which could be read correctly in 0.4 second while stationary on the ground required 1.0 second in flight [25]. This will result not only in increased error but also increased reaction time.

One final point regarding vibration: Most HMD designs are exit pupil forming systems. They can, in a very loose analogy, be compared to knotholes in a fence. To have an unobstructed view, you must put, and keep, your eye in the knothole. The exit pupil is the HMD's knothole. To prevent vignetting of the full image, the aviator must keep his eye within the exit pupil. If the exit pupil is large enough, additional vibrational effects can be ignored. However, if the exit pupil is small, then the eye may move out of it under the influence of vibration.

### 2.4 Sensor Switching

The current version of the Comanche HIDSS expects to provide both $I^2$ and FLIR imagery. While the final decision on whether the $I^2$ sensor(s) will be aircraft- or head-mounted is yet unknown, the current HIDSS design is based on all sensors being mounted on the aircraft. If, at a later date, a decision is made to mount the $I^2$ sensor(s) on the helmet, then aviators will be in a situation where they will be switching back and forth between sensor imagery originating from two different perspectives [13]. The human's basic visual sensors are his/her eyes. Prior to encountering aircraft-mounted sensors, his experience in perception and interpretation of visual information has been referenced to the eye's position on the head. When flying the Apache, the imagery often is from the FLIR sensor. This sensor is located on the nose of the aircraft and is approximately 10 feet forward and 3 feet below the aviator's design position. This exocentric positioning of the imagery source can introduce problems of apparent motion, parallax, and incorrect distance estimation [26]. However, this mode of sensor location does offer the advantage of allowing the aviator to have an unobstructed view of the area directly in front of and under the aircraft. This "see-through" capability is very useful when landing must be made in cluttered or unfamiliar landing areas.

If the FLIR remains exocentrically located and the $I^2$ sensor(s) is integrated into the HIDSS, then additional issues associated with mixed sensor location modes and the resulting switching of visual reference points must be considered. One study [27] looking at these potential issues was conducted using the AH-64 with its exocentrically located FLIR and several HMDs with integrated $I^2$ sensors. The study found significant degradation in performance for all maneuvers, regardless of direction of switching. Over 80% of the aviators reported that targets appeared to be at different distances as a result of switching, targets in the $I^2$ imagery appearing closer than in the FLIR imagery. Over a third (37%) of the aviators reported apparent changes in attitude or flight path when switching; three-fourths (75%) stated that switching caused disorientation in one or more of the maneuvers due to switching. And, of most concern, should be the fact that one-half (50%) had to transfer controls to the safety pilot during one of the maneuvers. All of the aviators in the study stated that sensor switching increased workload. In view of these results, careful consideration should be given to HMD designs which require the user to switch between noncollated sensor sources.

## 3. Optical Performance

In most HMD designs, an image source (e.g., CRT, LCD, etc.) creates on its face a reproduction of the outside scene. This reproduced image then is relayed through a set of optical elements (relay optics) producing a final image which is viewed by the eye. The former image on the image source has certain characteristics. The relay optics have a transfer function which modifies these characteristics in producing the final image. When the aviator dons the HMD, there are both system characteristics (e.g., FOV, magnification, see-through transmittance, etc) and image characteristics (relating to image quality) which define the usefulness of the HMD in helping the aviator perform the mission.

### 3.1 Image Quality

Farrell and Booth [28] define image quality as the extent to which a displayed image duplicates the information contained in the original scene in a form suitable for viewing and interpreting. [It should be noted that near-infrared (IR) and IR images are not normally viewed images.] To the user, image quality determines his ability to recognize and interpret information. For our purpose, we shall confine our discussion to the system's final image, which is defined by the image source and display optics. Numerous image quality FOMs have been developed and used to evaluate the physical quality of the image produced on a display with the goal of gauging user performance with the display. Task [29] provides an excellent summary of a number of FOMs which commonly are used for evaluating image quality in CRTs. These are listed in Table 2, categorized as geometric, electronic, and photometric.

Table 2: CRT display system FOMs.

| | | |
|---|---|---|
| **Geometric** | Viewing distance<br>Display size<br>Aspect ratio<br>Number of scan lines | Interlace ratio<br>Scan line spacing<br>Linearity |
| **Electronic** | Bandwidth<br>Dynamic range | Signal to noise ratio<br>Frame rate |
| **Photometric** | Luminance<br>Grey shades<br>Contrast ratio<br>Halation<br>Ambient illuminance<br>Gamma | Color<br>Resolution<br>Spot size and shape<br>MTF<br>Luminance uniformity |

FP technologies are being used as alternate HMD image sources. Klymenko et al. [30] have categorized FOMs for FPDs into four domains: spatial, spectral, luminance, and temporal (Table 3). These image domains parallel analogous human visual performance domains. The spatial domain includes those display parameters associated with angular view (subtense) of the user and coincide with the user's visual acuity and spatial sensitivity. The spectral domain consists of those parameters associated with the user's visual sensitivity to color (wavelength). The luminance domain encompasses those display parameters identified with the overall sensitivity of the user to illumination levels. The temporal domain addresses display parameters associated with the observer's sensitivity to changing levels of light intensity. [Baron [31] adds two additional domains: depth (3D) and noise.]

Table 3: FPD FOMs.

| | | |
|---|---|---|
| **Spatial** | Pixel resolution (H x V)<br>Pixel size and shape<br>Pixel pitch | Subpixel configuration<br>Number of defective (sub)pixels |
| **Spectral** | Spectral distribution | Chromaticity<br>Color gamut |
| **Luminance** | Peak luminance<br>Luminance range<br>Grey levels<br>Contrast (ratio) | Uniformity<br>Viewing angle<br>Reflectance ratio<br>Halation |
| **Temporal** | Refresh rate<br>Update rate | Pixel on/off response rates |

In general, these FOMs can be used for image quality evaluation for HMDs since the final image is that of the source image modified by the transfer function of the relay optics. However, there are a few additional FOMs which relate to the system as a whole. The FOMs selected for discussion here are not all inclusive but represent the most critical ones needed to effectively evaluate image quality. However, even for simple HMDs, these FOMs can fail to allow a user to judge between two competitive designs which significantly differ in scope and function [31].

#### 3.1.1 Contrast

Contrast refers to the difference in luminance between two (usually) adjacent areas. There is often confusion associated with this term due to the multiple FOMs used to express contrast [30]. Contrast, contrast ratio, and modulation contrast are three of the more common formulations of luminance contrast. The more common mathematical expressions for luminance contrast include:

$C = (L_t - L_b) / L_b$ for $L_t > L_b$ (Contrast)

$C_r = L_t / L_b$ for $L_t > L_b$ (Contrast ratio)

and

$C = (L_{max} - L_{min}) / (L_{max} + L_{min})$ (Modulation contrast)

where $L_t$ = target luminance, $L_b$ = background luminance, $L_{max}$ = maximum luminance, $L_{min}$ = minimum luminance, and $L_t > L_b$ and $L_{max} > L_{min}$.

Available contrast depends on the luminance range of the display. The range from minimum to maximum luminance values that the display can produce is referred to as its dynamic range. A descriptor for the luminance dynamic range within a scene reproduced on a CRT display is the number of shades of grey (SOG). SOG are luminance steps which differ by a defined amount. They are, by convention, typically defined as differing by the square-root-of-two (approximately 1.414).

Square-root-of-two SOG have been used historically for CRTs, which have enjoyed a position of preeminence as the choice for given display applications for decades. However, within the past few years, the FPD technologies have begun to gain a significant share of the display application market. Displays based on these various flat panel technologies differ greatly in the mechanism by which the luminance patterns are produced, and all of the mechanisms differ from that of CRTs. In addition, FPDs differ from conventional CRT displays in that most flat panel displays are digital with respect to the signals which control the resulting images. (Note: There are FPD designs which are capable of continuous luminance values, as well as CRTs which accept digital images.) As a result, luminance values for flat panel displays usually are not continuously variable but can take on only certain discrete values.

Confusion can occur when the term grey shades, historically used to express the number of discriminable luminance levels in the dynamic luminance range of analog CRT displays, is applied to digital FPDs. Since these displays, in most cases, can produce only certain luminance values, it is reasonable to count the total number of possible luminance steps and use this number as a figure of merit. However, this number should be referred to as "grey steps" or "grey levels," not "grey shades." For example, a given LCD may be specified by its manufacturer as having 64 grey levels. The uninitiated may misinterpret this as 64 shades of grey, which is incorrect. Its true meaning is that the display is capable of producing 64 different electronic signal levels between, and including, the minimum and maximum values, which generally implies 64 luminance levels. If one insisted on using a SOG figure of merit for discrete displays, it would appropriately depend on the value of the 1st and 64th levels.

### 3.1.2 Contrast and HMDs

HMDs introduce additional contrast issues. For example, in IHADSS, the sensor imagery is superimposed over the see-through view of the real world. Although see-through HMD designs are effective and have proven successful, they are subject to contrast attenuation from the ambient illumination. The image contrast as seen through the display optics is degraded by the superimposed outside image from the see-through component which transmits the ambient background luminance. This effect is very significant during daytime flight when ambient illumination is highest.

A typical HMD optical design in a simulated cockpit scenario is shown in Figure 3. The relay optics consist of two combiners, one plano and one spherical. Light from the ambient scene passes through the aircraft canopy, helmet visor, both combiners, and then enters the eye. Simultaneously, light from an image source such as a CRT partially reflects first off of the plano combiner and then off of the spherical combiner, and then is transmitted back through the plano combiner into the eye. The resulting image is a combination of the modified ambient (outside) scene and CRT images. Nominal values for the transmittances and reflectances of the various optical media are: 70% canopy transmittance; 85% and 18% transmittance for a clear and shaded visor, respectively; 70% transmittance (ambient towards the eye); 70% reflectance (CRT luminance back towards the eye) for the spherical combiner, 60% transmittance (ambient towards the eye) and 40% reflectance (CRT luminance) for the plano combiner.

Ambient scene luminances vary greatly over a 24-hour period. They can range from 0.001 fL under moonless, clear starlight conditions to 10,000 fL for bright daylight. Daytime luminances begin at approximately 300 fL. The image source used in Figure 3 is a miniature CRT. Depending on viewing time, day versus night, luminance values provided by the CRT and its associated optics can be selectively ranged from 10 fL (for night use) to an optimistic 1600 fL (for day use). A luminance of 800 fL may be a more typical daytime value.

Image contrast during night operations is usually not a problem. However, the use of HMDs for daytime imagery (versus for symbology) is not well defined. Based on the design in Figure 3 and the nominal values provided, Table 4 provides the theoretical values for Michelson contrast ($C_m$), contrast ratio ($C_r$), and SOG for various combinations of visors, ambient scene luminances, and CRT display luminances. In these equations, the ambient luminance reaching the eye assumes the role of the background luminance and the sum of the CRT and background luminances reaching the eye assumes the role of the target luminance.

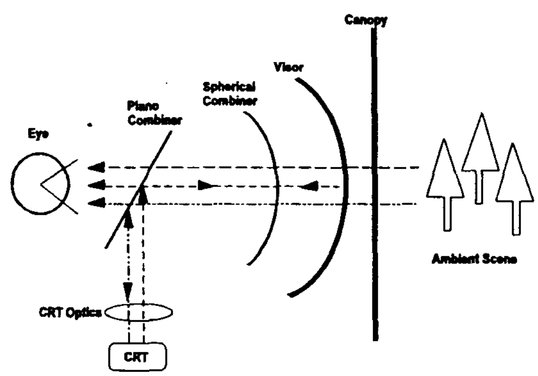


Figure 3. Typical catadioptric HMD optical design.

### 3.1.3 Contrast Requirements

Once appropriate figures of merit have been established for quantifying contrast, an obvious question is what are their recommended values. Unfortunately, there is no single value or set of values, for minimum contrast requirements. The amount of contrast required to perform a task on a display depends on numerous factors. These factors include the type of visual task (e.g., rapid target detection or status indicators), the viewing environment (e.g., ambient light level, presence of glare sources, the size and distance of the display, etc.), the nature of the displayed information (e.g., text, symbology, video, graphics), and the other display characteristics (such as screen resolution, blur and sharpness, jitter, color, pixel geometry, etc.).

Table 4: Michelson contrast, contrast ratio, and SOG values for an HMD design.

| | Ambient luminance | | | | | |
|---|---|---|---|---|---|---|
| | 3,000 fL | | 1,000 fL | | 300 fL | |
| Display luminance | Clear visor | Shaded visor | Clear visor | Shaded visor | Clear visor | Shaded visor |
| 100 fL | $C_m$ = 0.01<br>$C_r$ = 1.02<br>SOG= 1.06 | $C_m$= 0.05<br>$C_r$ = 1.11<br>SOG= 1.29 | $C_m$= 0.03<br>$C_r$ = 1.07<br>SOG= 1.19 | $C_m$= 0.14<br>$C_r$ = 1.32<br>SOG= 1.80 | $C_m$= 0.10<br>$C_r$ = 1.22<br>SOG= 1.59 | $C_m$= 0.35<br>$C_r$ = 2.06<br>SOG= 3.09 |
| 400 fL | $C_m$ = 0.04<br>$C_r$ = 1.09<br>SOG= 1.25 | $C_m$= 0.17<br>$C_r$ = 1.42<br>SOG= 2.02 | $C_m$= 0.12<br>$C_r$ = 1.27<br>SOG= 1.69 | $C_m$= 0.39<br>$C_r$ = 2.27<br>SOG= 3.37 | $C_m$= 0.32<br>$C_r$ = 1.90<br>SOG= 2.85 | $C_m$= 0.68<br>$C_r$ = 5.23<br>SOG= 5.79 |
| 800 fL | $C_m$= 0.08<br>$C_r$ = 1.18<br>SOG=1.48 | $C_m$= 0.30<br>$C_r$ = 1.85<br>SOG= 2.77 | $C_m$= 0.21<br>$C_r$ = 1.54<br>SOG= 2.25 | $C_m$= 0.56<br>$C_r$ = 3.54<br>SOG= 4.66 | $C_m$= 0.47<br>$C_r$ = 2.79<br>SOG= 3.97 | $C_m$= 0.81<br>$C_r$ = 9.45<br>SOG= 7.50 |
| 1600 fL | $C_m$= 0.15<br>$C_r$ = 1.36<br>SOG= 1.89 | $C_m$= 0.46<br>$C_r$ = 2.69<br>SOG= 3.87 | $C_m$= 0.35<br>$C_r$ = 2.08<br>SOG= 3.11 | $C_m$= 0.72<br>$C_r$ = 6.07<br>SOG= 6.22 | $C_m$= 0.64<br>$C_r$ = 4.58<br>SOG= 5.40 | $C_m$ = 0.89<br>$C_r$ = 17.91<br>SOG= 9.35 |

Despite the inability to establish a single set of contrast requirements, a considerable amount of research has gone into determining requirements for viewing and interpreting information in various display scenarios [28,32-33]. For example, for text to be legible on a directly viewed display, it is recommended that the modulation contrast for small characters (between 10 and 20 arc minutes) displayed on a monochrome CRT should be at least that defined by the equation:

$$C_m = 0.3 + [\, 0.07 * (20 - S)],$$

where S is the vertical size of the character set, in minutes of arc [34]. This equation is based on studies by Crook, Hanson, and Weisz [35] and Shurtleff and Wuersch [36].

Fortunately, even with the absence of well defined minimum contrast values, several rules of thumb can be applied. For displayed text, the above recommendation of a minimum contrast ratio value of 3:1, with 7:1 as the preferred value, can be used in benign viewing conditions. For displayed video, a minimum of six SOG is recommended.

## 3.2. Resolution and Modulation Transfer Function (MTF)

The most frequently asked HMD design question is "How much resolution must the system have?" Resolution refers to the amount of information (detail) which can be presented. This will define the fidelity of the image. Spatial resolution is, perhaps, the most important parameter in determining the image quality of a display system. An HMD's resolution delineates the smallest size target which can be displayed. An image's resolution usually is given as the number of vertical and horizontal pixels which can be presented.

In HMDs using CRTs as the image source, the CRT's resolution is the limiting resolution of the system. The CRT's horizontal resolution is defined primarily by the bandwidth of the electronics and the spot size. Vertical resolution is usually of greater interest and is defined mostly by the beam current diameter and the spreading of light when the beam strikes the phosphor, which defines the spot size (and line width). CRT vertical resolution is usually expressed as the number of raster lines per display height. However, a more meaningful number is the raster line width, the smaller the line width, the better the resolution. Twenty µm is the current limit on line width in miniature CRTs.

In discrete displays such as FPDs, resolution is given as the number of horizontal by vertical pixels. These numbers depend on the size of the display, pixel size, spacing between pixels, and pixel shape [37].

In any optical imaging system, we want the eye to be the limiting resolution factor. At an adaptation level of 100 fL, the eye can detect approximately 1.72 cy/mr (which equates to 20/20 vision). Ideally, the HMD should match or exceed this value. A more realistic, but still optimistic, goal for HMD resolution in the central area of vision is 0.91 cy/mr, with values between 0.39 and 0.77 cy/mr being acceptable [38].

Expressing resolution only in terms of the number of scan lines or addressable pixels is not a meaningful approach. It is more effective to quantify how modulation is transferred through the HMD as a function of spatial frequency. A plot of such a transfer is called a MTF curve. Since any scene theoretically can be resolved into a set of spatial frequencies, it is possible to use a system's MTF to determine image degradation through the system. If the system is linear, the system MTF can be obtained by convolving (multiplying) the MTFs of the system's individual components.

A CRT display's MTF curve typically is a monotonic function, maximum at the lowest spatial frequency present (determined by the display width) and decreasing to zero at the limiting highest spatial frequency of the display (Figure 4). A CRT display's MTF is defined by a number of factors: Scan rate, spot size, phosphor persistence, bandwidth, and drive level (luminance output). Investigations of the effects of these factors for currently used miniature CRTs can be found in Rash and Becher [39] and Beasley et al. [40].

Whether or not the MTF is a meaningful FOM for FPDs is still a point of contention within the HMD community. Biberman and Tsou [22] state that there is no "quantitatively useful" metric for measuring FP technologies which can be related to the MTF. However, Infante [41] provides the following explicit MTF expression for discrete displays:

$$MTF(u) = |(\sin \pi \sqrt{FF} x_p u) / (\pi \sqrt{FF} x_p u)| = |(\sin \pi x_a u) / (\pi x_a u)|$$

where $x_p$ is the pixel pitch, FF is the fill factor, and $x_a$ is the active pixel size.

Folding in the eyes response is important in assessing the "information transfer" a viewer can achieve. One image quality FOM based on taking the human visual system in consideration is the MTF area (MTFA). The MTFA was developed by Charman and Olin [42] and is pictured in Figure 4. The MTFA is the area bounded by the display system's MTF and the detection threshold curve for the human eye. Theoretically, the greater the MTFA, the greater the information perceived by the eye. The crossover point of the system MTF and the detection threshold curve defines the highest spatial frequency that can be detected (limiting resolution).

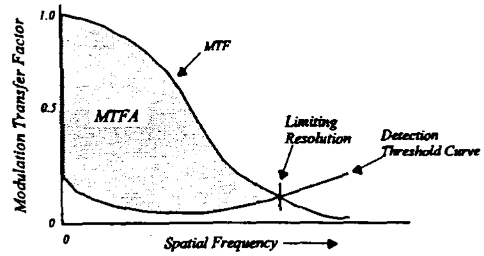

Figure 4. MTF and MTFA.

The MTFA, however, oversimplifies visual task performance and violates certain mathematical principles. Because of this oversimplification, other image quality metrics have been pursued. Of recent significance is the work of Peter Barten [43-44] and the "Square-root integral" (SQRI) assessment method.

The SQRI is given by

$$SQRI = \int \sqrt{(M(u)/M_t(u))} \frac{au}{u}$$

where M(u) is the MTF of the display, $M_t(u)$ is the visual contrast threshold curve, and u is spatial frequency per unit angle at the eye of the observer. The integration extends over the range from 0 to maximum spatial frequency. As with the MTFA, this equation takes into consideration the spatial frequency description of the display and the human visual system. Good agreement has been found between the SQRI and subjective measures of image quality [43-45].

Most MTF curves encountered are static MTFs, i.e., the modulation in the scene is not changing. However, while static targets relative to the ground do exist on the battlefield, in the aviation environment, relative motion obviously is the more prevalent condition. In addition to the relative target-aircraft motion, when VCSs are used, sensor gimbal jitter and head motion are present. When motion is present, the temporal characteristics of the scene modulation interact with those of the imaging system (e.g., scan rate and phosphor persistence for CRTs) and the transfer of modulation from the scene to the final display image can be degraded.

Phosphor persistence is an important display parameter affecting temporal response in CRT displays. Excessive persistence reduces modulation contrast and causes a reduction of grey scale in a dynamic environment where there is relative motion between the target and the imaging system [46]. Persistence effects can cause the loss of one or more grey steps. This may not be a concern at low spatial frequencies, where there may be multiple grey steps. But, where there is only enough modulation contrast to provide one or two grey steps under static conditions, the loss of even one grey step at high spatial frequencies would be significant.

This effect is well demonstrated in the history of the IHADSS. A P1 phosphor initially was selected to satisfy the high luminance daytime symbology requirement. After initial flight tests, the CRT phosphor was changed to the shorter persistence (1.2 msec) P43 phosphor because of reported image smearing. Test pilots reported tree branches seemed to disappear as pilots moved their heads in search of obstacles and targets. It was determined the longer persistence (24 msec) of the P1 phosphor was responsible for the phenomenon [13].

The degradation in image contrast due to temporal factors is not limited to CRT displays. Active matrix liquid crystal displays (AMLCDs) are currently the leading FP display and are frequently used to present moving imagery [47]. The liquid crystal molecules require a finite time to reorient themselves when the pixel is changing. This is a physical limitation. A response time of 20 - 100 msec is typical. This value is defined by the pixel access time (relatively short, ~65 µsec), crystal's response speed, and other LCD physical properties such as the dependence of cell capacitance on drive voltage and temperature [47-48].

Rabin and Wiley [49] compared visual performance between CRT and liquid crystal displays for high rates of image presentations and found a significant difference, which was attributed to the display response speed. The study involved a target detection task for various horizontal target velocities presented on the IHADSS (using a P43 phosphor image source) and an AMLCD HMD developed by Honeywell, Inc., Minneapolis, Minnesota. Target recognition (contrast sensitivity) was found to be degraded for the AMLCD HMD for the three highest velocities tested (4.4-17.6 deg/sec).

### 3.3 Luminance Uniformity

Variation in luminance across a display image can be distracting [28]. Luminance uniformity across an image is best described by its absence or nonuniformity [50]. Three important types of nonuniformity are: Large area nonuniformity, small area nonuniformity, and edge discontinuity. Large area nonuniformity is a gradual change in luminance from one area of a display to another; e.g., center to edge or edge to edge. Small area nonuniformity refers to pixel to pixel luminance changes over a small portion of the image. Edge discontinuities occur over an extended boundary.

While uniformity requirements are still lacking in the classical literature, one such guidance is that the luminance at any two points within a flat field image shall not vary by more than 20% [4]. Farrell and Booth [28] suggest limiting small and large area nonuniformities to 10% and 50%, respectively. The HIDSS allows a 20% variation from the mean image luminance, which should be based on luminance readings of at least 9 or more equally spaced positions within the image. [In cases where the entire image area is not useable, variation can be based on only that portion which provides acceptable image quality.]

## 4. Field-of-View

FOV, as used here, refers to the display FOV, the horizontal and vertical angles the display image subtends to the eye. In terms of impact on performance, FOV can be considered to be as important as resolution and contrast. During night and foul weather flights with HMDs, the largest amount of visual information available to the aviator is provided via the display imagery. In principle, the larger the FOV, the more information available. The maximum FOV target value would be that currently achieved by the unobstructed human visual system.

The human eye has an instantaneous FOV that is roughly oval and typically measures 120° vertically by 150° horizontally. Considering both eyes together, the overall binocular FOV measures approximately 120° (V) by 200° (H) [51]. The size of the FOV that an HMD is capable of providing is determined by several sensor and display parameters including size, weight, placement, and resolution. All of the designs achieved so far provide restricted FOV sizes. As FOVs decrease, head motion becomes greater, increasing head and neck muscle fatigue. This also reduces the amount of background information about the area (target) of interest and induces "tunnel vision" [52].

A number of studies have been conducted in an attempt to understand the role of FOV in pilotage and targeting tasks. Sandor and Leger [53] looked at tracking with two restricted FOVs (20° and 70°). They found that tracking performance appeared to be "moderately" impaired for both FOVs. Further investigation on FOV targeting effects found negative impacts on coordinated head and eye movements [54] and reinforced decreased tracking performance with decreasing FOV size [55-56]. Kasper et al. [57] also examined the effect of restricted FOVs on rotary-wing aviator head movement and found that aviators respond to such restrictions by making significant changes in head movement patterns. These changes consist of shifts in the center of the aviator's horizontal scan patterns and movements through larger angles of azimuth. They also concluded that these pattern shifts are highly individualized and change as the restrictions on FOV change. This work was an extension of Haworth et al. [58] which looked at FOV effects on flight performance, aircraft handling, and visual cue rating.

Perhaps the most important FOV study to rotary-wing aviation is the Center for Night Vision and Electro-Optics, Fort Belvior, VA, investigation of the tradeoff between FOV and resolution [59]. In this study, five aviators using binocular simulation goggles, performed terrain flights in an AH-1S Cobra helicopter. Seven combinations of FOV (40° circular to 60° x 75°), resolutions (20/20 to 20/70), and overlap percentages (50% to 100%) were studied. They reported the lowest and fastest terrain flights were achieved using the 40° - 20/60 - 100% and 40° - 20/40 - 100% conditions, with the aviators preferring the wider (60°) condition. However, the author did not feel that the results justified increasing FOV without also increasing resolution.

Seeman et al. [38] recommend an instantaneous FOV of 50° (V) by 100° (H) for flight tasks involving control of airspeed, altitude, and vertical speed. This estimate does not include considerations for other flight tasks, such as hover. Current HMD programs are striving to produce FOVs of 60° or larger. However, even a 90° FOV does not provide all the visual cues available to the naked eye [60]. Both Haworth et al. [58] and Edwards et al. [61] found that performance gains could be tied to increasing FOVs up to about 60°, where performance seems to encounter a ceiling effect. This raises the question as to whether increased FOV designs are worth the tradeoff costs.

## 5. Exit Pupil

The exit pupil of an (pupil forming) HMD is the area in space where all the light rays pass; however, it often is pictured as a two-dimensional hole. To obtain the full FOV, the viewing eye must be located at (within) the exit pupil. Conversely, if the eye is totally outside of the exit pupil, none of the FOV is visible. As the viewer moves back from the exit pupil, the FOV will decrease. [The eye has an entrance pupil; when the exit pupil of the HMD is larger than the entrance pupil of the eye, the eye can move around without loss of retinal illumination or FOV [62].]

The exit pupil has three characteristics: Size, shape, and location. Within the limitation of other design confounds, e.g., size, weight, complexity, and cost, the exit pupil should be as large as possible. The IHADSS has a circular 10-mm diameter exit pupil. The HIDSS design exit pupil also is circular but with a 15-mm diameter. While systems with exit pupils with diameters as large as 20 mm have been built, 10 to 15 mm is the typical value [63]. Tsou [9] suggests that the minimum exit pupil size should include the eye pupil (~ 3 mm), an allowance for eye movements that scan across the FOV (~ 5 mm), and an allowance for helmet slippage (± 3 mm). This would set a minimum exit pupil diameter of 14 mm.

The exit pupil is located at a distance called the optical eye relief, defined as the distance from the last optical element to the exit pupil. This term has caused some confusion. What is of critical importance in HMDs is the actual physical distance from the plane of the last physical element to the exit pupil, a distance called the physical eye relief or the eye clearance distance. This distance should be sufficient to allow use of corrective spectacles, NBC protective mask, and oxygen mask, as well as, accommodate the wide variations in head and facial anthropometry. This has been a continuous problem with the IHADSS, where the optical eye relief value (10 mm) is greater than the actual eye clearance distance. This is due to the required diameter of the HDU objective lens and the bulk of the barrel housing. To overcome the incompatibility of spectacles with the small physical eye relief of the IHADSS, the Army has investigated the use of contact lenses [64-66]. While citing a number of physiological, biochemical and clinical issues associated with contact wear and the lack of reliable bifocal capability, the studies did conclude that contact lenses may provide a partial solution to HMD eye relief problems.

## 6. Monocular/Biocular/Binocular Considerations

HMDs can be classified as monocular, biocular, and binocular, referring to the presentation of the imagery by the HMD. As previously defined, monocular means the HMD imagery is viewed by a single eye; biocular means the HMD provides two visual images from a single sensor, i.e., each eye sees exactly the same image from the same perspective; binocular means the HMD provides two visual images from two sensors displaced in space. [Note: A binocular HMD can use a single sensor, if the sensor is somehow manipulated to provide two different perspectives of the object scene.] A biocular HMD may use one or two image sources, but must have two optical channels. A binocular HMD must have separate image sources (one for each eye) and two optical channels.

### 6.1 Monocular Issues

Monocular HMDs generally have smaller packaging, lighter weight, and lower design costs. Their smaller packaging permit them to be placed closer to the head, causing less reduction in visual field [67]. Their drawbacks include FOV limitations, small exit pupil, the potential for binocular rivalry, eye dominance problems, increased workload, and reduced reaction time [68]. The reduced FOV [30° (V) x 40° (H) for the IHADSS] results in the need for increased head movements. The small exit pupil size requires the display to be very close to the eye and requires a very stable head/HMD interface. Binocular rivalry causes viewing conflicts between the aided eye viewing the display imagery and the unaided eye viewing the outside world. [Rivalry would be a greater concern in monocular systems where one eye was totally occluded. Such is not the case for IHADSS, where the display eye has see-through capability.] When rivalry does exist, studies have shown that target recognition and visual performance in general decreases [69]. Eye dominance may influence visual performance, of critical interest if the monocular HMD design does not allow for user preference (such as in the IHADSS where the display is always mounted on the right eye).

When Hale and Piccione [70] performed an aviator assessment of the IHADSS, they found evidence of increased workload, visual and mental fatigue, and stress. They found that as a mission progressed, aviators experienced increased difficulty in switching between eyes for visual input. Aviators reported having to resort to extreme actions, such as closing one eye, to either suppress or produce attention switching. Aviators, also, reported visual fatigue from the display "brightness" in the aided eye.

During the first years of fielding the Apache, the training failure rate was high (~10%), and eye dominance was suggested as a probable cause. McLean [71] correlated data on 16 Apache aviators for multiple eye dominance tests. Results showed little correlation between tests. This was explained by the rationale that eye dominance itself is not a singularly defined concept and is task dependent. Also, data failed to show any before and after effects on eye dominance due to PNVS training.

### 6.2 Biocular/Binocular Issues

As previously discussed, perhaps the greatest disadvantage of monocular HMDs is their reduced FOVs. It is well documented that reduced FOVs degrade many visual tasks [55,72). In HMD designs, the size (diameter) of the eyepiece lens limits the available FOV.

It generally is agreed that most visual capabilities, e.g., detection, discrimination, recognition, etc., are improved when two eyes are used, as compared to one [73-75]. Using this logic and the FOV argument, current HMD designs are two-eye designs. If an HMD is a two-eye design, there are a number of parameters which must be considered. These include interpupillary distance (IPD), image alignment between the two eyes, and luminance balance [8]. Failure to pay proper attention to these and corresponding issues can result in retinal rivalry, eye strain, fatigue, and, if severe enough, diplopia.

#### 6.2.1 Biocular Tolerances

However, having two optical channels presents the opportunity to have disparities (mismatches) between the imagery presented to the two eyes. These disparities can be alignment errors or optical image differences. Alignment errors reflect lack of parallelism of the two optical axes and can be vertical, horizontal, and/or rotational. Optical image differences can be in contrast, distortion, size (magnification), and/or luminance [62]. These errors will exist. The question is what magnitude of disparity can be tolerated before performance noticeably degrades. These permissible differences are referred to as the optical tolerance limits for the HMD design.

Self [62] provides a review of optical tolerance studies conducted and standards developed before 1986. The results of the review are summarized in Table 5. Also included in Table 5 are more recent tolerance recommendations. It is important to note that users will have varying sensitivities to these tolerances.

Fusion, which is the human visual system's ability to perceive the two images presented as one, is somewhat tolerant. Therefore, some misalignment can be present. Such tolerance limits are not well defined, as can be seen from the wide variation in values in Table 5. Also, it is expected that tolerance limits will vary among individuals and decrease with exposure, fatigue, and hypoxia. The first signs of having exceeded tolerance limits will most likely manifest themselves in the onset of visual fatigue, eye strain, and headaches.

#### 6.2.2 Partial binocular overlap issues

The implementation of partial overlap to achieve larger FOVs brings with it certain additional concerns. Fragmentation of the FOV, luning, and changes in target detection capability can occur in HMDs employing partial overlap [76-78]. If both eyes see the identical full image in a binocular HMD, what is known as a full overlap FOV, then the overall FOV is limited to the size of each of the monocular fields. If for design reasons, the size of the monocular fields are at a maximum and can not be increased without incurring unacceptable costs such as reduced spatial resolution, or increased size and weight of the optics, then the size of the full overlap FOV may not be sufficient.

Table 5: Summary of binocular optical tolerance limits [62].

| Vertical misalignment | Horizontal misalignment (Convergence) | Horizontal misalignment (Divergence) | Rotational difference | Magnification difference | Luminance difference |
|---|---|---|---|---|---|
| 8 arcminutes (2.3 mr) [79] | 22.5 arcminutes (6.5 mr) [79] | 7.5 arcminutes (2.2 mr) [79] | 10 arcminutes [80] | 2% [81] | 10% [81] |
| 14 arcminutes (4.1 mr) [82] | 28 arcminutes (8.1 mr) [82] | 14 arcminutes (4.1 mr) [82] | 2 degrees [83] | 2% [84] | 3% [85] |
| 17 arcminutes (4.9 mr) [81] | 2 arcminutes (0.6 mr) [85] | 4 arcminutes (1.2 mr) [85] | 29 arcminutes [28] | < 5% [84] | 5% [84] |
| 2 arcminutes (0.6 mr) [85] | 8.8 arcminutes (2.6 mr) [86] | 3.4 arcminutes (1 mr) [80] | | < 0.8% [28] | < 50% [28] |
| 3.4 arcminutes (1 mr) [87] | 8.6 arcminutes (2.5 mr) [80] | 4.1 arcminutes (1.2 mr) [86] | | 0.28% [80] | 15% [88] |
| 19 arcminutes (5.5 mr) [88] | 2.7° (47.1 mr) [28] | 3.4 arcminutes (1 mr) [87] | | 10% [83] | |
| 3.4 arcminutes (1 mr) [80] | | | | | |

Note: Caution should be used in applying these values since they are based on studies of various optical devices and under different test conditions.

Partial overlap is a way to increase FOV without increasing the size of the two monocular fields. In such a case, the new wider FOV consists of three regions---a central binocular overlap region seen by both eyes and two flanking monocular regions, each seen by only one eye. There are perceptual consequences for displaying the FOV to the human visual system in this unusual way. These perceptual effects have been a concern to the aviation community because of the potential loss of visual information and the visual discomfort [89-93].

First, whereas the full overlap FOV consists of one extended binocular region, the partial overlap FOV consists of three regions, distinguished by how each stimulates the visual system. This can result in the visual fragmentation of the three regions into three phenomenally separate areas, separated by the binocular overlap borders. Since this is a non-veridical perception of what is in reality a continuous visual world, visual misinterpretations may result.

Second, luning may occur in the FOV of partial overlap displays. This is a temporally varying subjective darkening of the flanking monocular regions, most pronounced near the binocular overlap borders. This phenomenon, like visual fragmentation, is due to the nature of the dichoptic stimulation of the monocular regions, meaning that each eye is receiving dissimilar stimulation in corresponding locations, instead of the similar stimulation of normal unaided vision. In this situation, dichoptic competition occurs. Here, the monocular region of the FOV presents a portion of the visual world to one eye and the black background, rather than the visual world, to the other eye. This results in various forms of binocular rivalry, where these inputs compete for awareness with the inputs of each eye alternating in suppressing the input of the other eye. Phenomenally, this is experienced as the darkening effect of luning, which is most prevalent when the eye receiving the wrong image of the black background dominates and suppresses the eye receiving the right image of the visual world.

Third, this competing visual input can result in less detectable targets in the monocular regions of the partial overlap FOV [78]. Melzer and Moffitt [2] have proposed blurring the binocular edges or putting in dark contour lines to separate the binocular and monocular regions to alleviate the detrimental visual effects. In dichoptic competition, sharper edges are stronger competitors than smooth edges [94]. The blurring works by weakening the competitive dichoptic strength of the wrong image, and the placement of dark contours works by enhancing the strength of the right image. Klymenko et al. [95] have confirmed that the placement of contours reduces luning.

In view of these issues, it generally is recommended that full overlap be implemented wherever possible, unless the increased FOV provided by partial overlap is essential [96].

## 7. Visual Performance

The discussions of physical FOMs above does not attempt to relate the measured values to the visual performance of the user. However, in some cases, it was appropriate to provide limited comments on the impact of the FOMs on user visual performance. In the following sections, system performance as a function of user visual performance is explored in greater depth. The eye has its own transfer function which must be considered when the display image is viewed. Previously, the FOMs for displays were categorized into four domains: Spatial, spectral, luminance, and temporal (Table 3). These image domains parallel analogous human visual performance domains. The spatial domain includes those display parameters associated with angular view (subtense) of the user and coincide with user's visual acuity and spatial sensitivity. The spectral domain consists of those parameters associated with the user's visual sensitivity to color (wavelength). The luminance domain encompasses those display parameters identified with the overall sensitivity of the user to illumination levels. The temporal domain addresses display parameters associated with the observer's sensitivity to changing levels of light intensity.

The human eye has an extraordinary visual capability. It can perceive light within the spectral region of 0.38 μm (violet) to 0.78 μm (red). It consists of a central region, containing cone detectors, which provides detail and color perception (decreasing with decreasing cone density away from the center, fovea); and a peripheral region, containing rod detectors, which provides black and white perception and motion detection. The maximum sensitivity of the cones is about 555 nm and is 507 nm for the rods. The eye has 10 decades of dynamic sensitivity, which usually are divided into three ranges: Photopic (day), mesopic (twilight), and scotopic (night). Adaptation to these varying levels is achieved through photochemical changes and changing pupil diameter from 2.5 to 8.3 mm. The temporal integration time of the eye is about 200 msec. Its resolution capability (for sine waves) is better than 1.72 cy/mr. However, these characteristics vary with age and viewing conditions.

### 7.1 Visual Acuity

Visual acuity is a measure of the ability to resolve fine detail. Snellen visual acuity commonly is used and is expressed as a comparison of the distance at which a given set of letters is correctly read to the distance at which the letters would be read by someone with clinically normal vision. A value of 20/80 indicates an individual reads letters at 20 feet that normally can be read at 80 feet. Normal visual acuity is 20/20. Visual acuity, as measured through imaging systems, is a subjective measure of the user's visual performance using these systems. The acquisition is a primary performance task. For this task, a reduced acuity value implies the user would achieve acquisition at closer distances. The accepted high contrast acuity value for $2^{nd}$ and $3^{rd}$ $I^2$ systems are 20/60 and 20/40, respectively [13]. However, providing an acuity value for thermal (FLIR) systems is difficult since the parameter of target angular subtense is confounded by the emission characteristics of the target. However, for comparison purposes, Snellen visual acuity with the AH-64 PNVS/IHADSS is cited as being 20/60 [59].

It is well known that visual acuity with $I^2$ decreases with decreasing night sky illumination [97-99]. Rabin [100] explored the source of this decrease and determined the limiting factor to be the contrast attenuation in the $I^2$ devices.

### 7.2 Contrast sensitivity

The human visual system's ability to discern information from a displayed image is limited by its capacity to perceive differences in luminance within the image. These luminance contrasts demarcate the available pattern information of the image. Discounting color and temporal differences, image information is conveyed primarily by patterned contrast. Thus, the information that can be conveyed by a display to a human observer is fundamentally limited by the human ability to perceive contrast. Different magnitudes of contrast are required to perceive different images. For example, the image of a large sharply demarcated object may require less contrast than the image of a small blurry object. If the contrast in an image is too low, i.e., below the visual threshold for detecting contrast, the displayed information will not be perceived. To make appropriate use of the figures of merit describing image quality in terms of contrast, one must characterize the human limitations in detecting contrast. The ultimate goal is to ensure an appropriate match between the contrast in the image conveying the displayed information and the human perceiver's ability to use that contrast.

The smallest magnitude of contrast that can be detected is a just noticeable difference (jnd) between two luminances. A "jnd" is a threshold value that is typically defined as some percentage of the time that a stimulus is correctly detected, often arbitrarily set at 75%. In other words, a jnd of contrast is the threshold magnitude of the luminance difference between two areas that is required to just detect that difference. In order to understand the relevance of the luminances of a display in terms of human perception, the dynamic range of a display, the difference between the maximum and minimum luminances, can be defined, or scaled, in terms of the number of jnds within that range. The number of jnds from minimum to maximum luminance gives us the luminance range in human threshold units [101].

An efficient way of characterizing the contrast threshold responses of the human visual system is the contrast sensitivity function shown in Figure 5, where "contrast" refers to modulation contrast. This plots contrast threshold values as a function of target spatial frequency. Spatial frequency refers to the number of a periodic pattern's repetitions, or cycles, within a unit length. [This unit length is typically expressed as a degree of visual angle when the perceiver is emphasized or as a display width when the image is emphasized.] Contrast sensitivity (on the vertical axis) is the reciprocal of the contrast threshold. The curve indicates that the human visual system is maximally sensitive, i.e., requires the least contrast to detect the pattern's presence, for patterns with a spatial frequency somewhere between 2 and 5 cycles per degree of visual angle. Sensitivity drops off for lower and for higher spatial frequency targets. Sine wave targets smaller or larger than the optimum size need more contrast to be seen.

### 7.3 Depth Perception and Stereopsis

Depth perception is the ability to estimate absolute distances between an object and the observer or the relative distances between two objects (i.e., which is closer). The cues for depth

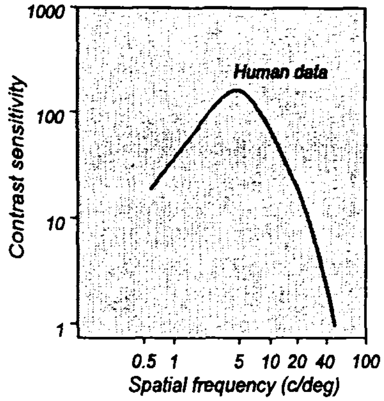


Figure 5. The human contrast sensitivity function.

perception may be monocular and/or binocular. Stereopsis is only a binocular perception and is the result of the two retinae slightly different images of the same object. The differences in the images occur due to the different location of the right and left eyes or the separation between the eyes.

Monocular cues for depth perception include geometric perspective, retinal image size, overlapping contours, shading or shadows, aerial perspective, motion parallax, etc. For Army aviation, motion parallax is considered the most important cue for depth perception. Closer objects appear to move more rapidly than distant objects with increasing displacements from the aircraft line of flight. Another form of motion parallax is referred to as optical flow or streaming.

Stereopsis is a binocular depth perception cue, requiring two slightly laterally displaced inputs for the eyes and sensors. Thresholds for stereopsis have been reported from 1.6 to 24 arcseconds, which is the difference in the eye convergence angles between two objects. For aviators, the passing value for stereopsis with the Armed Forces Vision Tester (AFVT) is 24 arcseconds (group D).

Wiley et al. [102] evaluated depth perception and stereopsis for the unaided eye and with the first fielded NVGs (AN/PVS-5) in both field and laboratory procedures using a modified Howard-Dolman apparatus in the laboratory at 20 feet and the same principle in the field with viewing distances from 200 to 2000 feet. The laboratory Howard-Dolman apparatus consists of two poles where the observer or the experimenter moves one pole to align in depth with a fixed pole, or the observer reports whether one pole is in front of the other with decreasing separation distances. For the field study, the targets were panels (3:1, height to width) and varied in height from 1.75 feet at 200 feet and 17.5 feet at 2000 feet to keep the target size in angular degrees constant. In the laboratory, the unaided photopic binocular threshold for stereo vision was 5 arcseconds and the NVG binocular threshold was approximately 18 arcseconds or similar to monocular unaided vision. Therefore, the conclusion that depth perception was degraded with NVGs implied that there was little or no stereopsis with NVGs. It is interesting to note that in the field study, the unaided monocular threshold was equal to or better than binocular depth perception at any of the tested distances from 200 to 2000 feet, and the NVG stereo threshold, although worse than the unaided thresholds in the field, was better than the unaided stereo threshold obtained in the laboratory.

The Integrated Night Vision Imaging System (INVIS) program attempted to design a night vision $I^2$ system with lower weight and improved center of mass for fixed-wing aircraft. The objective lenses and intensifier tubes were placed on the side of the helmet with a separation approximately 4 times wider than the average separation between the eyes. This wider than normal sensor separation induced a phenomenon called "hyperstereopsis," which is characterized by intermediate and near objects appearing distorted and closer than normal. The ground would appear to slope upwards towards the observer and appear closer beneath the aircraft than normal. On initial concept flights in an TH-1 helicopter (modified AH-1S Surrogate trainer for the PNVS) at Fort Belvoir, Virginia, pilots found the hyperstereopsis and sensor placement on the sides of the helmet shortcomings (major deficiencies) during terrain flight. The vertical supports in the canopy always seemed to be in the FOV with any head movement, and under starlight conditions, the pilots rated the hyperstereo system unsafe and terminated the study, except for demonstration rides [103].

A hyperstereopsis study was conducted at Fort Rucker, using an "Eagle Eye" NVG with a 2 to 1 increase in IPD, the Honeywell INVIS with 4 to 1 increase in separation, a standard ANVIS, and the FLIR as seen from the front seat in an AH-64 Apache [27]. The results showed no difference in flight performance among the different night imaging combinations. However, the pilots' subjective responses indicated they preferred the ANVIS. Aviators also reported they did not like switching from $I^2$ to FLIR imagery during landing phases, primarily because of the poor resolution of the FLIR compared to the $I^2$ devices.

In a recent study, Crowley et al. [104] compared the differences in 13 Army aviators' ability to judge and maintain height above terrain using binocular unaided day vision, 40-degree FOV day vision, ANVIS monocular night time, ANVIS binocular night time, and FLIR (PNVS) monocular night time. Aircraft type was an AH-1 Cobra equipped with an Apache FLIR and extensive data collection capability (radar altimeter). Instrument information or flight symbology on the FLIR image for altitude was removed. The results showed that subjects performed poorly when asked to provide absolute altitude estimates under any condition, but were more consistent in estimating changes in altitude. Performance with the FLIR was consistently worse than with the other viewing conditions. The authors attributed the more variable results with the FLIR to poorer resolution and changing thermal conditions over the 1½- year data collection period.

### 7.4 Visual Illusions and Spatial Disorientation

Spatial disorientation (SD) is defined by Benson [105] as "the situation occurring when the aviator fails to sense correctly the position, motion, or attitude of his aircraft or of himself within the fixed coordinate system provided by the surface of the earth and the gravitational vertical." Often included in the definition of SD is Vyrnwy-Jones' [106] clause: "the erroneous perception of the aviator's own position, motion, or attitude to his aircraft, or of his aircraft relative to another aircraft." In addition, contact with an obstacle known to be present, but erroneously judged to be sufficiently separated from the aircraft, is included as SD.

One might infer that flight with current night vision devices would induce some SD due to their limitations of reduced FOV, decreased resolution, reduced depth perception, and lack of color vision, as compared to unaided vision. However, at terrain altitudes at night, the aviator has essentially no FOV, resolution, depth perception, or color vision with the dark adapted eye, and could not survive in modern warfare without these night vision devices. Training and improved technology are required to reduce the necessary risks associated with night and adverse weather flying.

In many respects, visual illusions could be considered one of the primary causes of spatial disorientation with night vision devices. Crowley [107] conducted a survey soliciting information from 223 individuals on sensory effects or illusions that aviators had experienced with night vision systems. Frequently reported illusions were misjudgments of drift, clearance, height above the terrain, and attitude. Also reported were illusions due to external lights, and types of illusions were similar for both $I^2$ devices and the monocular IHADSS, although the sample size for the Apache pilots was small (n = 21). The illumination levels reported when illusions occurred with $I^2$ devices were below 24% moon, or less, for 36% of the illusion incidents, with lower percentages for incidents with increasing illumination. It would be easy to infer that low illumination was a causal factor, where actually the reverse is true. Illumination below 24% moon occurs 70% of the time for flights beginning 1 hour after sunset and lasting 4 hours. This is the typical Army NVG training mission. The most frequently cited methods to compensate for the illusions were to transfer the controls to the other pilot, use other aircrew to crosscheck visually, and to increase visual scan.

From 1987 to 1995, 37% of the 291 NVG accidents involved spatial disorientation [108]. An analysis of SD accidents of U.S. Army helicopters from 1987 to 1995 found the following results: The types of SD events for night aided flights, listed by frequency of occurrence, were (1) Flight into the ground (28%), (2) drift descent in hover (27%), (3) recirculation (brownout, whiteout, etc.) (22%), inadvertent entry to instrument meteorological conditions (8%), and (4) flight over water (3%) [109-110]. These percentages of SD occurrences were similar for all accidents except the rate for accidents with $I^2$ devices and FLIR were higher than for day flight. However, it should be noted that all U.S. Army night aided flights occur at 100 feet above ground level (AGL) or less except when transitioning to and from the primary airfields. This low altitude reduces reaction time and increases the risks compared to day and night general flight profiles. The 1987-1995 SD study [109] also found that very few illusions actually caused SD accidents.

### 7.5 Visual Problems

The use of HMDs increases visual workload and, very likely, raises stress levels among users. After several years of fielding the AH-64 Apache, a survey of Apache aviators [70] documented reports of physical fatigue and headaches following flights using the monocular IHADSS HMD. This followed anecdotal reports of similar problems from instructor pilots at Fort Rucker, Alabama. Hale and Piccione [70] cited as possible causes: binocular rivalry, narrow FOV, poor depth perception, inadequate eye relief, and overall system discomfort. To investigate potential concerns of long-term medical effects of using the IHADSS, the U.S. Army Aeromedical Research Laboratory (USAARL), Fort Rucker, Alabama, conducted a three-part study [111]. The first part was a written questionnaire which served the purpose of documenting visual problems experienced by the local Fort Rucker, Alabama, Apache aviator community. The second part was a clinical and laboratory evaluation of the refractive and visual status of a sample of these aviators. The third part was an assessment of the diopter focus settings used by aviators in the field environment. Since the IHADSS is designed to have the virtual imagery appear at optical infinity, incorrect diopter focus settings could, in theory, lead to visual fatigue and related visual problems.

A total of 58 Apache aviator questionnaires were completed. More than 80% of the sample aviators reported at least one visual complaint associated with flying with the IHADSS. A summary of complaints is provided in Table 6 [111]. The most common complaint (51%) was that of "visual discomfort" during flight. Approximately a third of the aviators reported occasional headaches, and about 20% reported blurred vision and/or disorientation while flying. The percentage of aviators reporting headache and blurred vision after flying remained about the same, while the percentage of those experiencing disorientation after flying decreased to 5%.

The clinical and laboratory evaluation of the refractive and visual status of 10 aviators found no statistical correlation between visual performance and visual complaints. There were no significant differences found between right and left eye performance. There was evidence of mild incipient presbyopia in a majority of the aviators, but this was within expectations for the sample age range. Binocular ocular motility for the sample was found to be lower than expected. But, in summary, the study concluded there was no significant variation from normal performance values noted.

The diopter focus settings of 20 Apache aviators (11 students and 9 instructor pilots) were measured in the aircraft following their normal preflight setup. Nine were measured under nighttime illumination conditions and 10 under daytime conditions. A range in focus settings of 0 to -5.25 diopters (mean of -2.28 diopters) was obtained. It was concluded that the required positive accommodation by the eye to offset these negative focus settings was a likely source of headaches and visual discomfort during and following long flights. No correlation was found between the focus settings and aviator age or experience; nor were there differences between instructor pilots and students, or day versus night.

In another survey [107] of 242 aviators flying either ANVIS (rotary- and fixed-wing) or IHADSS, a very small percentage of the rotary-wing ANVIS users (n = 212) reported physiological effects to include eyestrain (3%), headache (2%), motion sickness/vomiting (2%), postflight blurred vision (1%), and dizziness (1%); only 5% of Apache aviators (n = 21) reported any visual problems (that of dark adaptation effects).

The move towards two-eyed (binocular) wide FOV HMDs may result in adverse visual effects if care is not taken in their design. Mon-Williams, Wann, and Rushton [112] point out that conflicts between accommodation and vergence, focal error, and prismatic errors may result in "unstable binocular

Table 6: Apache aviator reports of visual complaints during and after flight [111].

| Complaint | During flight | | | After flight | | |
|---|---|---|---|---|---|---|
| | Never | Sometimes | Always | Never | Sometimes | Always |
| Visual discomfort | 49 % | 51 % | -- | 70 % | 28 % | 2 % |
| Headache | 65 % | 35 % | -- | 67 % | 32 % | 2 % |
| Double vision | 86 % | 12 % | 2% | 89 % | 9 % | 2 % |
| Blurred vision | 79 % | 21 % | -- | 72 % | 24 % | 3 % |
| Disorientation | 81 % | 19 % | -- | 95 % | 5 % | -- |
| Afterimages | NA | NA | NA | 79 % | 19 % | 2 % |

vision." As previously discussed, failure to maintain strict binocular alignment may introduce serious performance problems.

## 8. Conclusions

HMDs are continuing to expand their role and presence in the aviation community. It has been shown that HMDs provide unique and necessary capabilities to night and foul weather operations. It is the believed that this trend will continue.

Perhaps, the best design approach for HMDs is an integrated one, where the HMD is designed from the ground up, addressing the combined issues of acoustics, biodynamics and vision. The less preferred approach is that of adding the optical section of the HMD design to an existing helmet platform. This usually results in performance compromises.

The performance of an HMD depends on multiple factors, which include acoustical (e.g., sound attenuation, speech intelligibility, etc.) , biodynamic (e.g., head supported weight, center of mass, impact attenuation, etc.), and optical (e.g., distortion, power, magnification, etc).

While not necessarily of greater importance, HMD visual and optical design concerns have been identified and presented with an emphasis on impact on visual performance. As HMD designs move from the monocular IHADSS to the binocular HIDSS, issues of fusion, alignment, etc. require greater emphasis.

**Disclaimer**

The views, opinions, and/or findings contained in this paper are those of the authors and should not be construed as an official Department of the Army position, policy, or decision.

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